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HELIUM ISOTOPES AND TECTONICS IN SOUTHERN ITALY

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Abstract. Geodynamic evolution of southern Italy can be understood within the framework of the Mediterranean-Alpine System. Subduction of a plate along the Sicily-Calabrian forearc under the Tyrrhenian Sea has been suggested by many geophysicists, although it is not yet confirmed and remains somewhat controversial. Helium isotope ratios provide useful information on the geotectonic structure of the region. We report here the $^3He/^4He$ ratios of terrestrial gas samples from southern Italy. The observed $^3He/^4He$ ratios are relatively high in the Eolian volcanic arc region and low in the other areas. Dichotomous explanations are presented. Firstly volcanic arc-forearc hypothesis suggests the subduction along the Sicily-Calabrian forearc. Secondly horizontal transport hypothesis is described based on the relationship between the ratios and radial distance from the recent spreading basin in Southern Tyrrhenian Sea.

Introduction

Compressional deformation of the European Alpine belt had been predominatingly associated with continent/continent collisions since Tertiary. After the period, the region has been changed to extensional tectonics and the subsidence has also developed within the orogenic belt of the Mediterranean region [Dewey et al., 1973]. Thus, the Mediterranean-Alpine System shows a complex geological pattern and is characterized by the development of various local centers of spreading and of subduction. Among these smaller scale motions, the Tyrrhenian Sea and the Sicily-Calabrian forearc is distinguished since the region exhibits a geodynamic scheme of trench-arc-marginal basin system. The existence of a Wadati-Benioff zone dipping under the Tyrrhenian sea was reported [Gasparini et al., 1982]. The crustal structure changes from continental sense in the Apulian region to oceanic in the Tyrrhenian Sea [Morelli et al., 1975]. The terrestrial heat flow values are low in the Sicily-Calabrian forearc and high in the Tyrrhenian sea [Loddo and Mongelli, 1979]. All these features suggest a plate subduction beneath the sea. Thus the Eolian volcanic Islands such as Vulcano, Lipari, and Salina are considered to be arc volcanism.

In contrast to Pacific-type island arc volcanics, however, low potassium content rocks (a characteristic feature of island-arc tholeiites) are extremely scarce in the Eolian Islands [Barberi et al., 1974]. The strontium isotope ratios of these rocks show higher values than those of Pacific volcanics [Stern, 1982]. These signatures conflict with the above geophysical hypothesis. Recently a more complicated volcano-tectonic pattern than the subduction hypothesis was presented. The marked curvature of the Eolian volcanic chain can be explained by the occurrence of crustal shear processes followed by strike-slip movement leading to a clockwise rotation of Sicily [Ghisetti and Vezzani, 19821. This hypothesis is not yet fully confirmed.

In the light of knowledge accumulated during previous investigations [Lupton, 1983; Mamyrin and Tolstikhin, 1984], a correlation between helium isotope ratios and geotectonic environments has been pointed out. Intensive surveys carried out in circum-Pacific subduction zones have revealed a clear geographical pattern in the $^3He/^4He$ ratios [Sano and Wakita, 1985; Sano et. al., 1987]. Higher $^3He/^4He$ ratios than the atmospheric ratio are generally found in volcanic arc and backarc regions, suggesting an emanation of the Earth's primordial helium from the mantle; relatively low $^3He/^4He$ ratios observed in the forearc region are attributable to the radioactive decay of uranium and thorium in crustal rocks.

Hooker et al. [1985] published helium isotope data in Italy and discussed crust - mantle interaction in the region. We report here further helium isotope data in southern Italy, which provides useful information on the geotectonic setting of the region as well as an important clue to understanding the Alpine-Mediterranean System.

Experimental

We have collected 18 terrestrial gas samples (see Figure 1.) using a lead glass container with two vacuum valves. In the laboratory about 0.5 cm^3STP of each gas sample was introduced into a metallic vacuum line and purified using hot titanium-zirconium getter and two charcoal traps held at 77 K. The $^4He/^{20}Ne$ ratios were measured by a quadrupole mass spectrometer (QMG112, Balzers). Helium was completely separated from neon by a cryogenic charcoal trap held at 40 K and transferred into a high precision mass spectrometer (modified VG5400, VG Isotopes). Ion beams of $^3He^+$ and $^4He^+$ were detected with a double collector system at the same time. Resolving power of about 550 at 5% peak height was attained for complete sepa-

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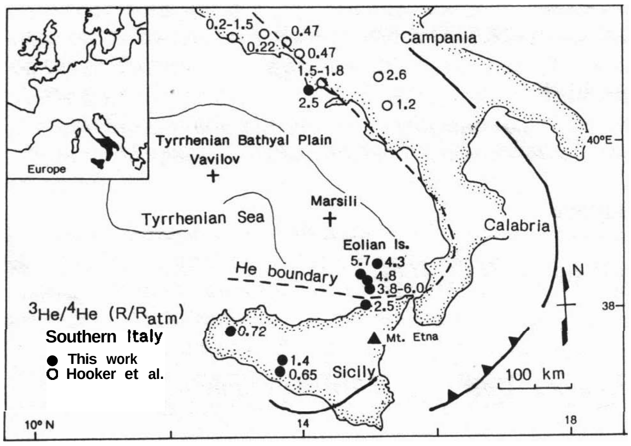

Fig. *1.* Geographical distribution of the $^3He/^4He$ ratios in southern Italy. Solid circles show the ratio obtained in this work, open circles are data reported by ***Hooker et al.*** **[1985].** A helium boundary (a dashed line) is based on the distribution of $^3He/^4He$ ratios. A solid line is external front of the Metaponto and Gela nappe referred to ***Ghisetti and Vezzani*** **[1982].**

ration of $^3He^+$ beam from those of H3+ and HD+ with a flat peak shape. Atmospheric helium was used as a running standard. A detailed description of the measurement has been given elsewhere ***[Sano and Wakita,*** **1988].**

Results and Discussion

Table *1* lists the measured $^3He/^4He$ and $^4He/^{20}Ne$ ratios, together with the location and sampling date. Errors on the helium isotope ratios are one standard deviation, including the statistical error of an individual run and the error of the air standard measurement to which the $^3He/^4He$ ratio is calibrated. Errors on the $^4He/^{20}Ne$ ratios were estimated to be about ***10 % [Sano and Wakita,*** **1988].** The observed $^3He/^4He$ ratios vary from ***0.654*** R_{atm} (where R_{atm} is the atmospheric $^3He/^4He$ ratio, ***1.40*** x ***10-6)*** to ***5.97*** R_{atm}. The highest value *(5.97* R_{atm}) in Vulcano fumarole is identical to those usually found in circum Pacific volcanic zones such as Kamchatka ***[Kamenskiy et al.,*** **1976],** Japan ***[Nagao et al., 1981;*** ***Sano and Wakita,*** **1985],** Mariana ***[Craig et al.,*** **1978],** New Zealand ***[Torgersen et al., 1983; Sano et al.,*** **1985],** and Colombia [***Williams et al.,*** **1987].**

Sampling sites and corrected $^3He/^4He$ ratios (R/R_{atm}) are shown in Figure *1* together with data in Campania region reported by ***Hooker et al.*** **[1985].** All samples from Eolian islands have $^3He/^4He$ ratios significantly higher than the air. High $^3He/^4He$ ratios strongly suggests the contribution of mantle-derived helium, which may be the result of magmatic volatiles in these samples. The $^3He/^4He$ ratios in Sicily and Campania regions are relatively low with values up to ***2.6*** R_{atm}. Low $^3He/^4He$ ratios may be attributed to a significant dilution by radiogenic helium generated within the continental crust. The contribution of tritiogenic helium may be negligibly small because of high helium contents observed in samples studied.

Two hypotheses are offered to explain the geographical distribution of terrestrial $^3He/^4He$ ratios in southern Italy. First is a volcanic arc - forearc concept and second is a horizontal transport model from the southern Tyrrhenian Sea.

Firstly the idea of the helium boundary was stimulated

Table *1.* $^3He/^4He$ and $^4He/^{20}Ne$ ratios in terrestrial gases from southern Italy

No.	Name	Location N. E	Date	$^3He/^4He$ ($\times 10^{-6}$)	$^4He/^{20}Ne$	(R/R_{atm})	$(R/R_{atm})_c$
1	Vulcano fumarole	38" 25′, 14" 58'	Feb. 5, 1984	3.31 ± 0.06	0.46	2.36	5.4
			Feb. 5, 1984	7.13 ± 0.11	230	5.09	5.1
			May 28, 1986	8.23 ± 0.05	180	5.88	5.9
			May 28, 1986	8.36 ± 0.07	150	5.97	6.0
2	Vulcano sea side	38° 25′, 14° 58'	May 10, 1983	5.29 ± 0.05	45	3.78	3.8
			May 28, 1986	6.76 ± 0.04	31	4.83	4.9
			Oct. 19, 1986	6.76 ± 0.05	14	4.83	4.9
			Oct. 19, 1986	5.31 ± 0.11	5.9	3.79	3.9
3	Vulcano mud pool	38" 25′, 14" 58'	May 10, 1983	5.22 ± 0.16	43	3.73	3.8
			May 25, 1986	6.67 ± 0.04	17	4.76	4.8
4	Lipari	38° 30′, 14° 57'	May 28, 1986	6.75 ± 0.06	80	4.82	4.8
5	Salina	38" 35′, 14° 50'	Oct. 5, 1986	8.00 ± 0.05	73	5.71	5.7
6	Panarea	38° 38′, 15" 3'	Jun. 25, 1986	6.01 ± 0.04	300	4.29	4.3
7	Pozzuoli	40" 46′, 14" 6'	May 13, 1983	3.48 ± 0.04	330	2.49	2.5
8	Segesta	37° 56′, 12° 50'	May 24, 1986	1.01 ± 0.01	39	0.721	0.72
9	Aragona	37° 24′, 13" 36'	May 24, 1986	0.915 ± 0.008	>3000	0.654	0.65
10	Aquapia	37" 32′, 13° 38'	May 24, 1986	1.91 ± 0.01	16	1.36	1.4
11	C. Calava	38" 11′, 14" 55'	May 27, 1986	3.43 ± 0.02	15	2.45	2.5

$R/R_{atm} = (^3He/^4He)_{obs}/(^3He/^4He)_{air}$

$(R/R_{atm})_c = [(R/R_{atm})_{obs} - r]/(1 - r)$

$r = (^4He/^{20}Ne)_{air}/(^4He/^{20}Ne)_{obs}$

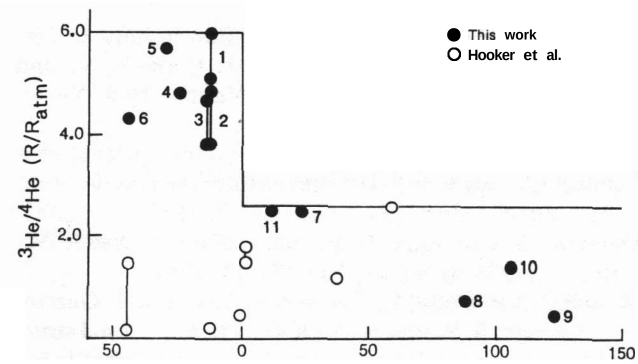

Fig. 2. The $^3He/^4He$ profile of southern Italy showing $^3He/^4He$ ratio versus geographical distance from sampling site to the helium bundary. Solid circles show the ratio obtained in this work, open circles are data reported by Hooker et al. [1985]. Samples #1-#6 are from Eolian Islands.

by the recent recognitions of distinctive spatial relationships between $^3He/^4He$ ratios and proximity to the helium boundary in NE Japan [Sano and Wakita, 1985] and to that in the North Island of New Zealand [Sano et al., 1987]. Based on the geographical distribution of the $^3He/^4He$ ratio, we tentatively draw a helium boundary, about 100 km inward, parallel to the Sicily- Calabrian forearc (see Figure 1). The boundary coincides well with the 50 mW/m^2 heat flow contour in Italy [Loddo *and Mongelli*, 1979] and with post-Tortonian and recent magmatic arcs. Both heat flow and $^3He/^4He$ ratio are high inside and low outside this helium boundary.

Helium isotope ratios are plotted in Figure 2 as a function of relative distance from the helium boundary to the sampling site. In the forearc region, about 100 km outward from the boundary, the ratios are as low as 1.5 Ratm. Assuming that the magmatic and crustal $^3He/^4He$ ratio are 1.1×10^{-5} and 2×10^{-8}, respectively, the contribution of magmatic helium is less than 20 % in the area. In contrast, the $^3He/^4He$ ratios in the volcanic arc region vary from 0.2 R_{atm} to 6.0 R_{atm}. High $^3He/^4He$ ratios are from Eolian island samples, while every ratio less than air is from the Campania area. There is a contrast in $^3He/^4He$ ratio between the forearc and volcanic regions in the Sicily-Calabria arc system. The step-like pattern (Figure 2) is somewhat similar to those found in NE Japan arc [Sano and Wakita, 1985] and the North Island of New Zealand [Sano et al., 1987], although the high $^3He/^4He$ ratios are only found in the area around Vulcano while all the rest of Italy has low $^3He/^4He$ ratio. Recently Tedesco et al. [1989] have found high $^3He/^4He$ ratio of up to 3.2 R_{atm} in a submarine fumarole of the Gulf of Pozzuoli, close to Napoli. The site is located in the volcanic arc side of the helium boundary and the value is higher than the highest $^3He/^4He$ ratio in the forearc side of the boundary [Hooker et al., 1985]. This result may imply that the step-like pattern is applicable to the Southern Italy. In order to verify this pattern, measurements of volcanic rocks as well as pore water of sea sediment from the Tyrrhenian Sea are highly desirable.

The step like pattern (Figure 2) can be explained by a mechanism invoking the presence or absence of a magma in the shallow region of the crust. The uprising magma is the probable carrier of primordial helium and heat from the upper mantle in volcanic arcs. High $^3He/^4He$ ratios in volcanic arc are derived from the magma. In forearc region, lack of magma makes crustal helium contribution dominant, which leads to the low $^3He/^4He$ ratios in the samples.

Taking the subduction hypothesis, genesis of the southern Tyrrhenian Sea is explained by a backarc spreading related to the subduction of a plate along the Sicily-Calabrian forearc. Since the permeation velocity of helium in crustal rock is low, mantle helium should be transferred by a material flow such as an uprising magma. The geographical distribution of the $^3He/^4He$ ratio likely reflects presence or absence of magma.

Magmatism of Mt. Etna is a major exception of a geodynamic scheme of the forearc - volcanic arc - marginal basin system in the region, since the volcano is situated in forearc region of Sicily. The volcanism is attributed to some shear lines and tensional stress fields [Horvath and Berck*hemer*, 1982; Loddo and Mongelli, 1979], but the details are not well known. *Allard* (personal communication) reported a $^3He/^4He$ ratio of 5.9 R_{atm} measured in lava-flow gases of Mt. Etna. *Polyak* et al. [1979] also found the high $^3He/^4He$ ratio of 6.6 R_{atm} in Mofette Palici nearby Mt. Etna. These high ratios are identical to the Eolian samples, suggesting subduction type helium in the samples derived from the upper part of the mantle, but the detail is not clear. Future work should provide some constraints on the genetic problem of Mt. Etna.

The second explanation for the geographical distribution of $^3He/^4He$ ratios is based on the upwelling mantle in the Tyrrhenian Bathyal Plain (Figure 1). The two areas surrounding the Vavilov and Marsili Seamounts in the southern Tyrrhenian Sea show the thinnest oceanic crust, (8 - 10) km and the highest heat flow values, > 200 mW/m^2 [*Della* Vedova et al., 1984]. The ages of these two volcanic edifices are very young (< 2.4 m.y. for the Vavilov Seamount and < 0.2 m.y. for the Marsili Seamount [*Barberi* et al., 1977]), suggesting that the opening of the southern Tyrrhenian Sea is very recent. The observed $^3He/^4He$ ratios decreases as the radial distance from the Tyrrhenian Bathyal Plain increases, following a roughly exponential law. The primordial helium carried by upward-moving convective currents of the mantle in the southern Tyrrhenian Sea is then distributed by horizontally. Farther from the Tyrrhenian Bathyal Plain, larger the dilution by the crustal helium with low $^3He/^4He$ ratio is suggested. There are close correlations among the radial distance from the Tyrrhenian Bathyal Plain, the $^3He/^4He$ ratio, the terrestrial heat flow value [Loddo and Mongelli, 1979; *Della* Vedova et al., 1984], and the crustal thickness [*Morelli* et al., 1975; *Boccaletti* et al., 1984], supporting the horizontal distribution of convective mantle currents in the region.

Williams et al. [1987] reported that the $^3He/^4He$ ratios of terrestrial gases and fluids decrease with increase of radial distances from the central cone of Nevado del Ruiz volcano, colombia, following a roughly exponential law. The data suggest that mantle helium can be carried the appropriate radial distances by a hydrothermal system. Although the distance in the present case is significantly larger than that of Colombia, the similar explanation can also be applicable to southern Italy. The validity of this implication, however, needs to be tested by the accumulation of further geological, geophysical and geochemical data.

In conclusion, the geographical distribution of helium isotope ratios in southern Italy provides useful information on the geotectonic setting and testable hypotheses. The subduction of a plate along the Sicily-Calabrian forearc and the upwelling mantle beneath the Tyrrhenian Bathyal Plain can both be applied to explain the observed $^3He/^4He$ distribution.

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